

Room temperature electrically tunable broadband terahertz Faraday effect

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The terahertz (THz) frequency range (0.1-10 THz) fills the gap between the microwave and optical parts of the electromagnetic spectrum. Recent progress in the generation (1) and detection (2) of the THz radiation has made it a powerful tool for fundamental research and resulted in a number of applications (3; 4). However, some important components necessary to effectively manipulate THz radiation are still missing. In particular, active polarization and phase control over a broad THz band would have major applications in science and technology. It would, e.g., enable high-speed modulation for wireless communications (5) and real-time chiral structure spectroscopy of proteins and DNA (6; 7). In physics, this technology can be also used to precisely measure very weak Faraday and Kerr effects, as required, for instance, to probe the electrodynamics of topological insulators (8; 9). Phase control of THz radiation has been demonstrated using various approaches. They depend either on the physical dimensions of the phase plate (and hence provide a fixed phase shift) (10; 11; 12) or on a mechanically controlled time

delay between optical pulses (and hence prevent fast modulation) (13; 14; 15). Here, we present data that demonstrate the room temperature giant Faraday effect in HgTe (16) can be electrically tuned over a wide frequency range (0.1-1 THz). The principle of operation is based on the field effect in a thin HgTe semimetal film. These findings together with the low scattering rate in HgTe open a new approach for high-speed amplitude and phase modulation in the THz frequency range.

The idea behind our experiments is to exploit the strong interaction between a solid-state plasma and THz radiation (17). Because of this interaction, left- and right-handed circularly polarized THz waves have different complex refraction indices when a magnetic field is applied (18). Recently, this characteristic property has been proposed to realize broadband THz modulators and phase plates based on electron-doped InSb crystals (19). However, there are two problems in the realization of such devices for practical applications. First, the giant Faraday effect in InSb does not survive at room temperature. Second, this approach requires fast modulation of the applied magnetic field with an amplitude of several hundreds mT, which is a rather challenging demand.

In semimetals with zero (or very small) band gap, such as HgTe, the electron plasma exists in undoped samples, due to the thermal activation of electrons. The ability to use such undoped HgTe layers results in a very high electron mobility and, consequently, we have been able to demonstrate the giant Faraday effect even at room temperature (16).

To achieve control over the Faraday effect in a constant magnetic field, we have now fabricated devices fitted with transparent gate electrodes, which allow to change the carrier density and thus the properties of the electron plasma in the HgTe layer. By applying a moderate voltage $|U| < 1$ V to these gates we are able to control the Faraday rotation and Faraday ellipticity, i.e., amplitude, phase shift, and polarization of the THz radiation at room temperature.

The THz experiments have been carried out in Faraday geometry as shown schematically

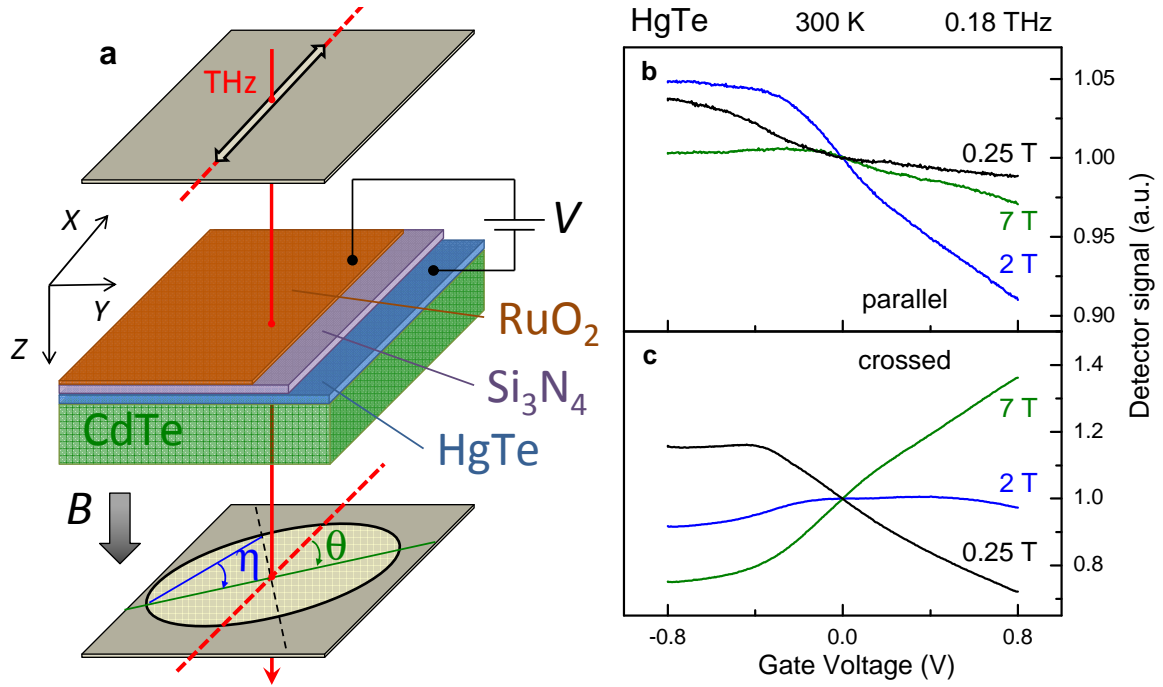


Figure 1: *Electric voltage control of THz radiation.* (a) - Schematic representation of experimental arrangement to control the Faraday rotation (θ) and Faraday ellipticity (η) by a gate voltage. (b,c) - Normalized detector signal as function of gate voltage in a geometry with parallel (b) and crossed (c) polarizers, respectively.

in Fig. 1a. In this geometry the external magnetic field is parallel to the propagation direction of the THz radiation. The incident polarization is linear and the polarization of the transmitted radiation is detected by a wire grid analyzer. Further experimental details are given in the Supplementary Material. All experiments presented here have been carried out at room temperature. Our estimations suggest that the concentration of carriers confined to the topological surface state in this material (9; 20) is comparable with the concentration of carriers occupied bulk states.

As shown in Fig. 1bc, we observe a substantial variation of the amplitude of the transmitted signal as a function of gate voltage, both in parallel (t_p) and in crossed (t_c) polarizer geometry. Consequently, the Faraday rotation and ellipticity can be controlled by using a moderate electric voltage. In a first approximation, the observed changes may be attributed to the gate dependence of the effective charge density in the HgTe film. As will be shown below, not only the density, but all electrodynamic parameters of the HgTe are affected by the gate voltage. We mention already at this point that the response of the THz signal is asymmetric with the sign of the gate voltage, which is probably due to carrier trapping at the interface between HgTe and the gate insulator. We also observed hysteresis effect when tuning the gate voltage beyond certain critical value.

In order to characterize the electron dynamics in HgTe under applied gate voltage, a set of experiments at different magnetic fields B and THz frequencies ω has been carried out. Figure 2 demonstrates the magnetic field dependencies of the magnetooptical signal of the HgTe film at three different gate voltages. The transmission amplitude for parallel polarizers (Fig. 2a) shows a clear minimum at a frequency-dependent field position which corresponds to the cyclotron resonance in HgTe $\Omega_c = \omega$. The width of the minimum in t_p is directly connected to the scattering rate of electrons. As the width in Fig. 2a changes strongly with gate voltage, a variation of the characteristic scattering time τ is evident.

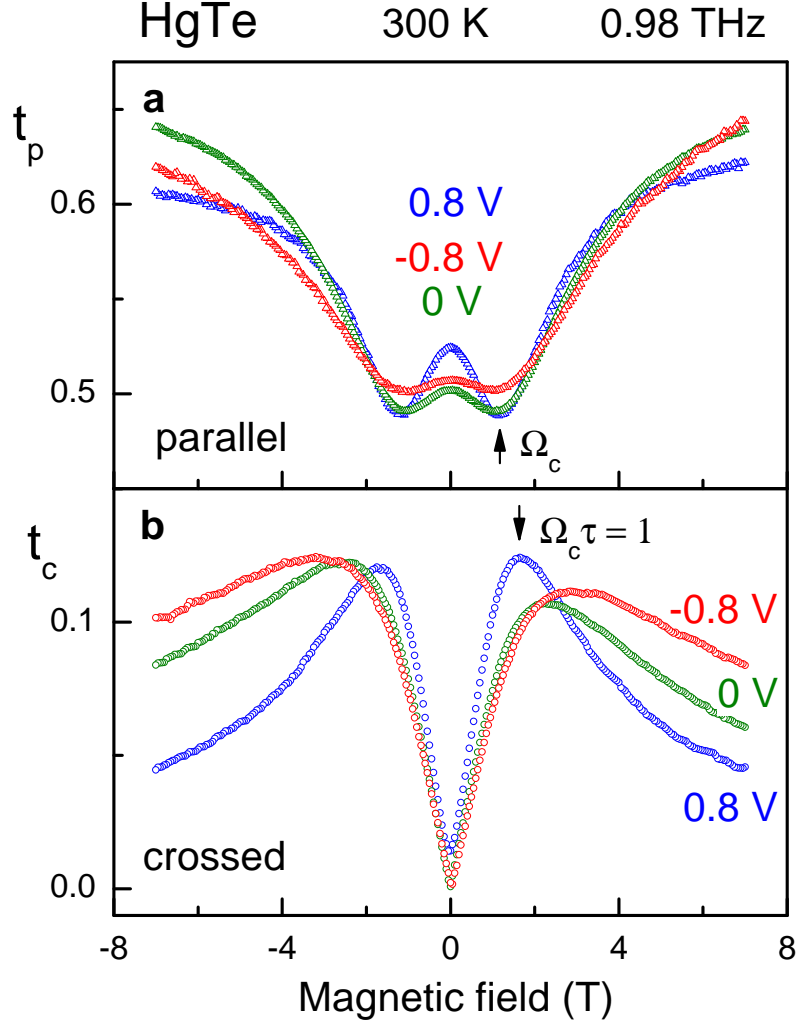


Figure 2: *Magneto-optic transmittance of the HgTe film.* Magnetic field dependent amplitude of the transmitted radiation in Faraday geometry and for different gate voltages as indicated. **(a)** - Transmission in parallel polarizers geometry. The arrow marks the position of the cyclotron resonance $\omega = \Omega_c$. **(b)** - Transmission in crossed polarizers. The maximum indicated by the arrow allows a determination of the quasiparticle scattering time τ .

Figure 2b shows the amplitude of the transmission in crossed polarizer geometry. All curves reveal a characteristic maximum at a magnetic field around ± 2 T. As shown in the Supplementary material [Eq. (10)], this maximum corresponds to a field value of $\Omega_c \tau = 1$ and it allows for an independent determination of τ . Again, a strong variation of the maximum is observed in the field dependence of t_c , which confirms the variation of the scattering time with gate voltage.

In addition to the transmission amplitude, phase information has been obtained using a Mach-Zehnder interferometric arrangement. From these experiments, the polarization state of the transmitted THz radiation can be fully polarized, including Faraday rotation and ellipticity. These data are shown in Fig. 3 for the parameter range accessible in our setup ($|B| < 7$ T and $|U| < 0.8$ V). The data in Fig. 3 are given for two different frequencies, close to the upper and the lower limits of our spectrometer. From the Faraday ellipticity vs. Faraday rotation diagram of Fig. 3 one can see that a desired polarization state can be set by varying either magnetic field or gate voltage.

The observed gate dependence of the magnetooptical spectra can be well interpreted within the Drude model. The details of the characterization procedure and extraction of the electrodynamic parameters are given in the Supplementary Material. In brief, we fit simultaneously the magnetic field dependencies using charge density (n_{2D}), scattering rate ($1/\tau$) and cyclotron frequency (in terms of Ω_c/B) as the only fitting parameters. By repeating this fit for different gate voltages, we determine how these parameters depend on U , as shown in Fig. 4. Two-dimensional electron conductivity derived from the other parameters as

$$\sigma_{2D} = en_{2D} \frac{\Omega_c}{B} \tau \quad (1)$$

is also shown in Fig. 4.

As expected, a strong variation of the electron density with gate voltage (nearly a factor of two) is observed (Fig. 4a). Assuming the simple capacitor formula $\Delta n_{2D} = \varepsilon_0 \varepsilon_{\text{Si}_3\text{N}_4} \Delta U / d_{\text{Si}_3\text{N}_4}$

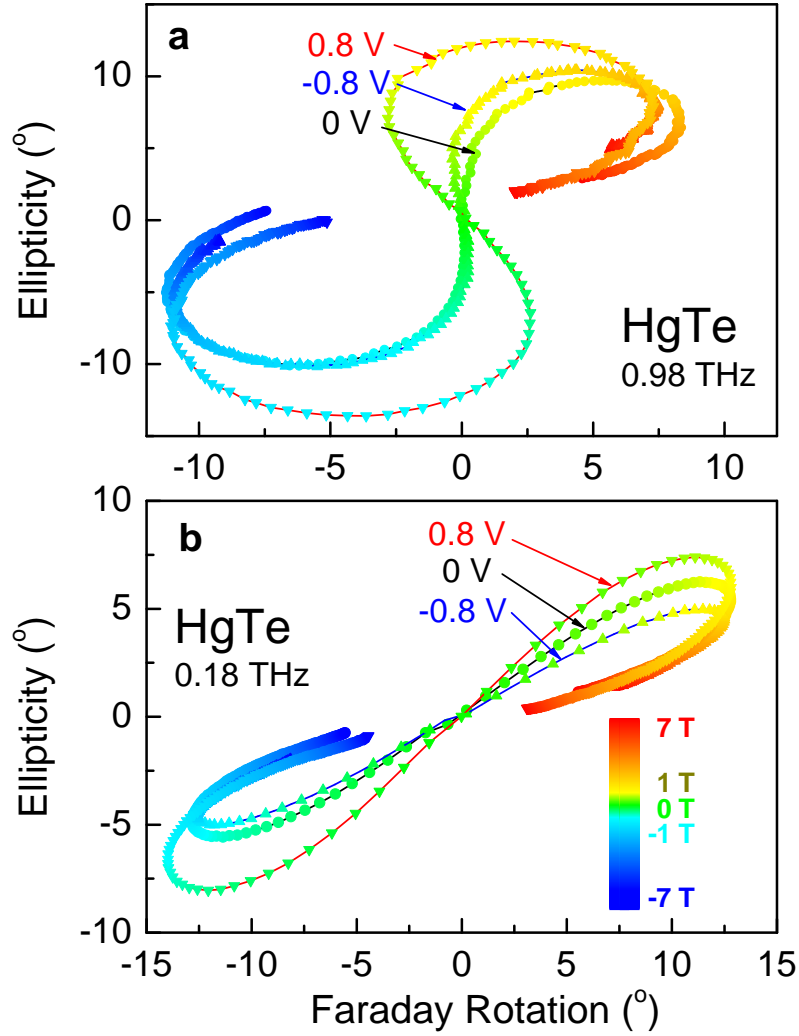


Figure 3: *Tunability of Faraday rotation and ellipticity.* Parametric presentation of the attainable range of Faraday rotation and ellipticity for different fields and voltages at 0.98 THz (a) and 0.18 THz (b), respectively. The data are shown as magnetic field dependent polarization states at three different gate voltages, as indicated. The values of the external magnetic field are color-coded. Symbols - experiment, lines are a guide to the eye.

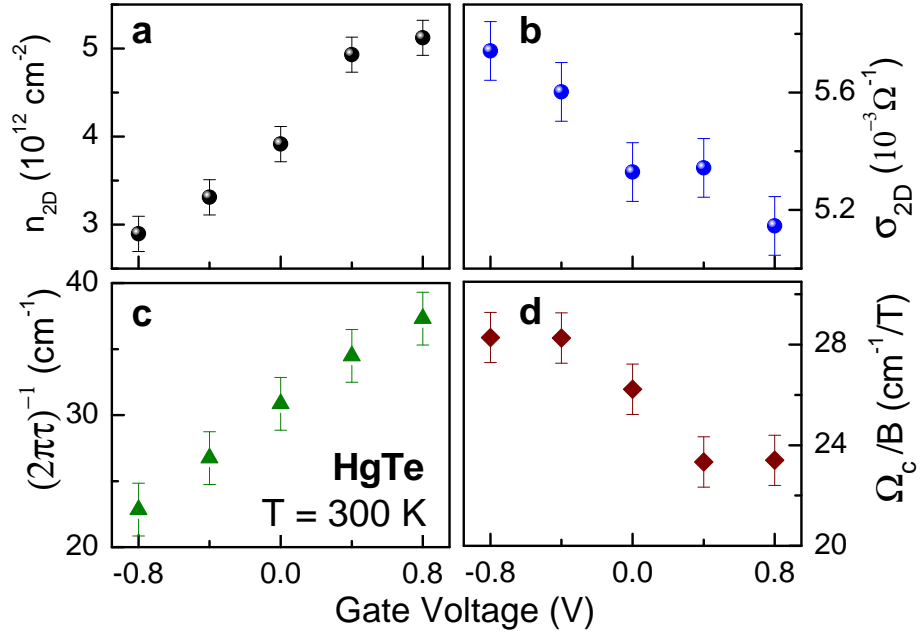


Figure 4: *Gate dependence of the electrodynamic parameters.* Electrodynamic parameters of the conduction electrons in HgTe at room temperature as obtained from Faraday rotation and ellipticity. **a** - Effective two-dimensional electron density. **b** - Two-dimensional dc conductivity. **c** - Electron scattering rate. **d** - Cyclotron resonance frequency.

to estimate the density variation, we obtain $\Delta n_{2D} \simeq 4.15 \cdot 10^{12} \text{ cm}^{-2}$ per Volt. Here ε_0 is the permittivity of the free space and $\varepsilon_{\text{Si}_3\text{N}_4} = 7.5$ is the dielectric constant of Si_3N_4 insulating layer. This is in a reasonable agreement with our experimentally observed value of $1.12 \cdot 10^{12} \text{ cm}^{-2}\text{V}^{-1}$. Where again the difference with the capacitor model likely results from carrier trapping at the $\text{HgTe}/\text{Si}_3\text{N}_4$ interface.

Contrary to the increase of the electron density with the gate voltage, the conductivity (σ_{2D} , Fig. 4b) is a decreasing function of U . This is rather unusual and can conceivably be explained by increased carrier scattering (τ^{-1} , Fig. 4c) at the $\text{HgTe}/\text{Si}_3\text{N}_4$ interface for larger gate voltages. Finally, we observe that the cyclotron frequency depends on the gate voltage as well, Fig. 4d. This result is expected for the Dirac surface states in HgTe with $\Omega_c/B \propto 1/\sqrt{n_{2D}}$. It can be also caused by the deviation from ideal parabolic dispersion of bulk electrons in HgTe .

All results presented here have been obtained at room temperature, suggesting practical applications, such as fast phase and amplitude modulation or direct control of the polarization state by gate voltage and/or magnetic field. As the observed tuning of the THz radiation is due to modulation of the electron conductivity in the HgTe layer and is obtained by purely electrical means, it should be possible to achieve rather high modulation speed, comparable to this obtained with high electron mobility transistors (HEMT). The modulation amplitude is as large as several degrees per Volt, and we believe that it can be further improved by optimizing parameters of the gate material, insulating barrier and HgTe layer.

Acknowledgements

This work was supported by the by the German Research Foundation DFG (SPP 1285, FOR 1162) the joint DFG-JST Forschergruppe on 'Topological Electronics', the ERC-AG project '3-TOP', and the Austrian Science Funds (I815-N16).

Supporting Online Material

The sample studied in this work is a coherently strained 100-nm-thick nominally undoped HgTe layer, grown by molecular beam epitaxy on an insulating CdTe substrate (21). A 3 nm thin RuO₂ layer has been used as a gate electrode and 10 nm thick Si₃N₄ layer as an insulating barrier. The gate electrode transmits approximately 80 % of the terahertz radiation and revealed no own Faraday rotation signal. The amplitude of the gate voltage has been limited to ± 0.8 V to avoid an electrical breakdown of the insulating layer.

Transmittance experiments at terahertz frequencies ($0.1 \text{ THz} < \nu < 1 \text{ THz}$) have been carried out in a Mach-Zehnder interferometer arrangement (22; 23) which allows measurement of the amplitude and phase shift of the electromagnetic radiation in a geometry with controlled polarization. Using wire grid polarizers, the complex transmission coefficient can be obtained both in parallel and crossed polarizers geometry. Static magnetic fields, up to ± 7 Tesla, have been applied to the sample using a split-coil superconducting magnet.

To interpret the experimental data we use the ac conductivity tensor $\hat{\sigma}(\omega)$ obtained in the classical (Drude) limit from the Kubo conductivity of topological surface states (see e.g. Ref. (24)). The diagonal, $\sigma_{xx}(\omega)$, and Hall, $\sigma_{xy}(\omega)$, components of the conductivity tensor as functions of THz frequency ω can be written as:

$$\sigma_{xx}(\omega) = \sigma_{yy}(\omega) = \frac{1 - i\omega\tau}{(1 - i\omega\tau)^2 + (\Omega_c\tau)^2} \sigma_0, \quad (2)$$

$$\sigma_{xy}(\omega) = -\sigma_{yx}(\omega) = \frac{\Omega_c\tau}{(1 - i\omega\tau)^2 + (\Omega_c\tau)^2} \sigma_0. \quad (3)$$

Here $\Omega_c = eBv_F/\hbar k_F$ is the cyclotron frequency, σ_0 is the dc conductivity, B is the magnetic field, v_F , k_F , e , and τ are the Fermi velocity, Fermi wave-number, charge, and scattering time of the carriers, respectively. For the Dirac spin-helical surface states the Fermi wave-number depends on the 2D carrier density, n_{2D} , through relation $k_F = \sqrt{4\pi n_{2D}}$, with no spin degeneracy. For massive carriers the cyclotron resonance frequency can be written as $\Omega_c = eB/m$,

where m is the effective electron mass in the parabolic approximation.

For a free standing film and neglecting any substrate effects, the complex transmission coefficients in parallel (t_p) and crossed (t_c) polarizers geometry can be written as:

$$t_p = \frac{4 + 2\Sigma_{xx}}{4 + 4\Sigma_{xx} + \Sigma_{xx}^2 + \Sigma_{xy}^2}, \quad (4)$$

$$t_c = \frac{2\Sigma_{xy}}{4 + 4\Sigma_{xx} + \Sigma_{xx}^2 + \Sigma_{xy}^2}. \quad (5)$$

Here Σ_{xx} and Σ_{xy} are effective dimensionless 2D conductivities, defined as: $\Sigma_{xx} = \sigma_{xx}dZ_0$ and $\Sigma_{xy} = \sigma_{xy}dZ_0$ with the HgTe film thickness $d = 100$ nm and the vacuum impedance $Z_0 \approx 377 \Omega$. In order to take into account the influence of the substrate a transfer matrix formalism (25; 26; 16) is utilized. The electrodynamic properties of the CdTe substrate are obtained in a separate experiment on a bare substrate.

According to Eq. (4), the transmittance in parallel polarizers (t_p) depends mainly on Σ_{xx} . The minima in $|t_p|$ roughly correspond to the cyclotron resonance energy and they scale with magnetic field. This may be understood by taking into account that for our film $\Sigma \ll 1$ and Eqs. (4,5) simplify to:

$$t_p \simeq 1 - \Sigma_{xx}/2; \quad t_c \simeq \Sigma_{xy}/2. \quad (6)$$

In the limit $\omega\tau \gg 1$, Eq. (2) may be approximated by

$$\sigma_{xx} \simeq \frac{1 - i\omega\tau}{(\Omega_c^2 - \omega^2)\tau^2} \sigma_0, \quad (7)$$

which leads to a resonance like feature in σ_{xx} and t_p for $\Omega_c = \omega$. Thus, the positions and widths of the minima in Fig. 2a are directly connected to Fermi velocity (v_F) for linear dispersion [or the effective mass (m) for parabolic dispersion] and the scattering rate (τ^{-1}) of the electrons.

The polarization rotation θ and the ellipticity η are obtained from the transmission data using:

$$\tan(2\theta) = 2\Re(\chi)/(1 - |\chi|^2), \quad (8)$$

$$\sin(2\eta) = 2\Im(\chi)/(1 + |\chi|^2) . \quad (9)$$

Here $\chi = t_c/t_p$ and the definitions of $\theta + i\eta$ are shown schematically in Fig. 1a. A direct interpretation of the complex Faraday angle is in general not possible because of the interplay of σ_{xx} and σ_{xy} in the data.

In the low frequency limit ($\omega\tau \ll 1$) Eq. (3) simplifies to the static result:

$$\sigma_{xy} = \frac{\Omega_c\tau}{1 + (\Omega_c\tau)^2}\sigma_0 . \quad (10)$$

The last expression has a maximum at $\Omega_c(B)\tau = 1$, which leads to maxima in t_c (Eqs. (5, 6) and Fig. 2b) and in θ at about the same field value. Therefore, the Faraday angle provides a direct and an independent way of obtaining the scattering rate $1/\tau$.

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